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AN EVALUATION OF SOLID STATE SUPERLATTICES FOR USE IN LABORATORY PROGRAMS

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ABSTRACT

We have performed an evaluation of solid state superlattices for use in laboratory programs. This evaluation consisted simply of a literature search on solid state superlattices, looking for basic theory papers and for novel devices and designs that could be useful for laboratory programs. While the bulk of these papers are directed towards fiber-optic communications (lasers and detectors) there was an amazing variety of proposed devices that could do everything from measuring the oxygen content in a hydrogen atmosphere to infrared detectors and microwave lenses. There are a large number of devices that show promise for use in laboratory programs, including: adjustable frequency infrared detectors, high-gain, low-noise electron multipliers, UV or X-ray light sources using non-relativistic electrons, low noise photon detectors or switches, microwave detectors/optical modulators, high frequency microwave oscillators, etc.

INTRODUCTION

A decade ago, a number of physicists began speculating about the properties of solid-state superlattices. The superlattices that they envisioned would consist of a number of thin, periodic layers of two different solid state materials (compositional superlattice) or of a single solid state material with thin periodic layers of two different dopings (doping superlattice). At the time, these materials could not be fabricated, however the physicists speculated that it would not be long before they would be.[1]

Since then, superlattices have been fabricated with molecular-beam epitaxy. Molecular-beam epitaxy is a fabrication technique where crystalline atomic layers are put down one at a time, at a rate of about one layer per second. With this technique, devices have been fabricated with material layers that are only four atomic layers thick (about 12 Å) with interfaces between layers consisting of a single atomic plane (Fig. 1).[2]

In this report we have evaluated solid state superlattices for use in laboratory programs. We have included a bibliography of selected papers and texts on the theory of superlattices and on specific device designs that would be useful for laboratory programs. For the most part, we ignored semiconductor lasers and laser detectors that were being developed for fiber-optic communications, as the volume of those reports is enormous. We did include some detector designs that we felt would be useful in laboratory programs. We have also included the basic theory and classifications of the solid state superlattice.

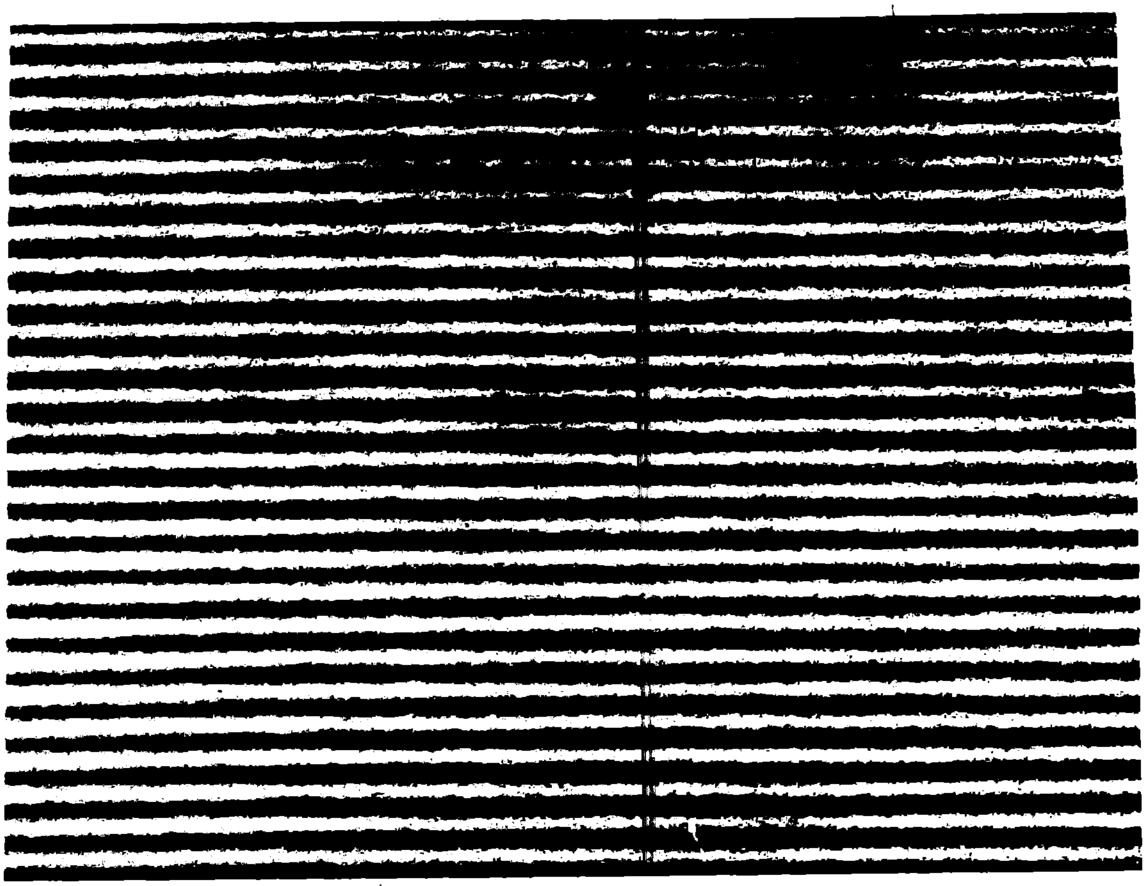


Figure 1 An electron micrograph of a solid state superlattice created with Molecular Beam Epitaxy. This superlattice consists of alternating layers of 6 atomic planes of GaAs (18 Å) and 4 atomic planes of $GaAl_xAs_{1-x}$ (12 Å). The interface between layers is only a single atomic plane thick (3 Å).

The most useful attribute of solid state superlattices is adjustability. By judicious choice of materials, dopings, layer thicknesses and applied voltages, the band gap, optical absorption coefficient, minority carrier lifetime, mobility, etc. may be selected. In other words, the device designer is no longer confined to using the fixed material properties of a small number of semiconductor materials.

PHYSICS AND CLASSIFICATION

As mentioned above, the solid state superlattice comes in two different material configurations: compositional and doping. There can also be combinations of materials and dopings. Note that there is no reason to be limited to two materials or dopings. Any number of different types of layers are possible. At the present time, we have not found any papers dealing with more than two different layers. The limiting factor as to what may be used in the different layers of a compositional superlattice is that the crystal structure must match close enough so that there will not be a significant amount of strain at the interface boundary. Otherwise, strain induced dislocations can cause significant trapping at the interface that will render a device useless.

In a normal semiconductor, most of a device's characteristics are determined by the valence band and the conduction band. These bands are the result of broadening of the discrete atomic energy levels when a large number of atoms are compressed into a solid. In a semiconductor, the valence band is generally filled with electrons (at 0 K), the conduction band is empty. The forbidden gap between these two bands is about 1 eV wide. Electron conduction can only take place in the conduction band and hole conduction can only take place in the valence band. The actual width of the forbidden gap and its shape in energy-momentum space determines most of the optical and transport properties of a material.

BAND STRUCTURE

In a superlattice, the alternating layers of semiconductor materials create a similar alteration in the bandstructure. This, in effect, creates a series of potential wells for electrons in the conduction band and for holes in the valence band. These potential wells then quantize the allowed energy levels, creating a series of energy levels within the well rather than a continuum of levels. Structures with boundary layers that are thicker than an electrons mean free path (> 100 Å), have little interaction between the different quantum wells and are known as quantum well structures (Fig. 2a). If the boundary layers are thinner than an electrons mean free path (< 100 Å), then the electron wave functions in the different quantum wells overlap, causing the the energy levels to broaden into a set of minibands. These are known as superlattice structures. Note that the minibands penetrate through the barrier layers (Fig. 2b) and that the effective masses of the carriers will decrease significantly.

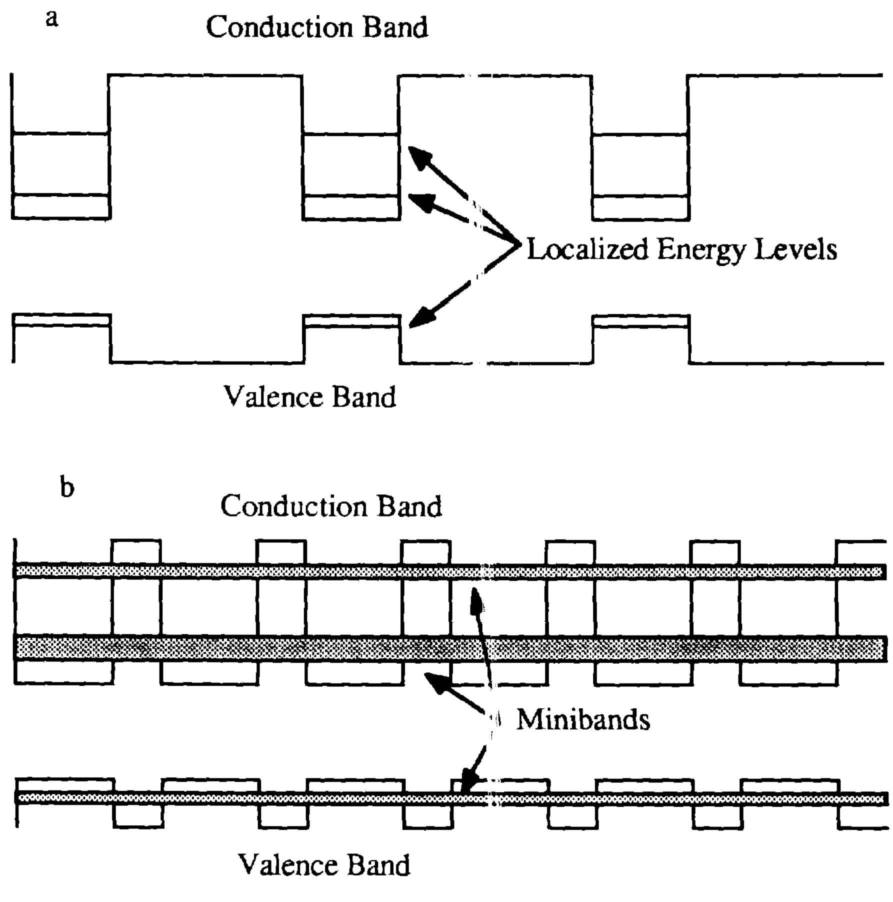


Figure 2 Two types of layered structures: a) Quantum well structure, characterized by thick barrier layers and non-interacting quantum wells; b) Superlattice structure, characterized by thin barrier layers and interacting quantum wells.

TYPES

Superlattice structures are broken down into three different types, depending on the relationship of the energy levels in the alternating materials[3]. Type I superlattices have alternating materials with different band gaps. The edges of the valence and conduction bands of the small band gap material are greater than and less than respectively, the edges of the valence and conduction bands of the wide bandgap material (Fig. 3a). This type is characteristic of undoped GaAs-GaAlAs superlattices. Type I' superlattices have the conduction and valence band edges of one material greater than the conduction and valence bands respectively, of the second material (Fig. 3b). This type of structure is also characteristic of modulation doped superlattices where the doping alternates between p-type and n-type. Type II superlattices have the conduction band edge of one material below the edge of the valence band of the second material (Fig. 3c). This creates a short between the conduction and valence bands at the material interfaces.

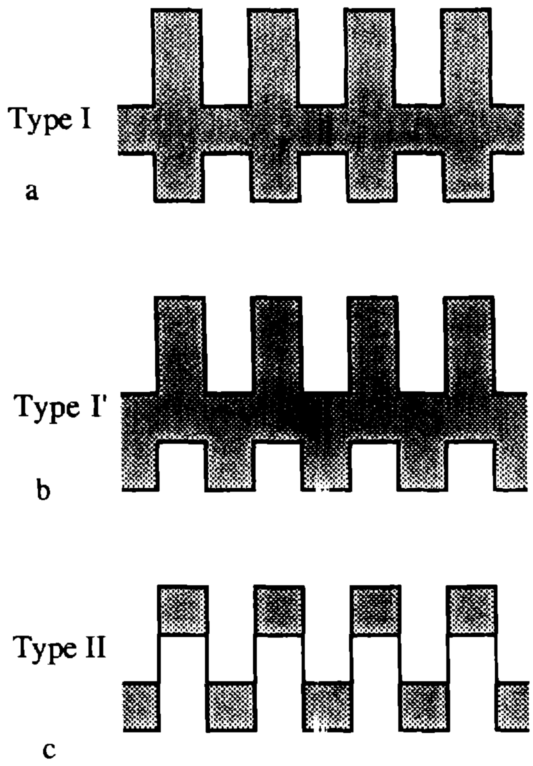


Figure 3 the three different types of superlattice bandstructure. a) Type I; b) Type I'; c) Type II.

CONDUCTION OF CARRIERS

Conduction of charge carriers (electrons and holes) in a normal semiconductor proceeds as in figure 4a. For example, an electorns is moved horizontally in the conduction band by the applied field until it emits a phonon, dropping it back down to the bottom of the conduction band. This motion continues across the device.

In a solid state superlattice,there are several different modes of conduction. At low voltages, electrons move along the minibands (miniband conduction) in the same manner as a normal semiconductor. As the applied voltage increases, the tilt in the miniband increases. Since the mini-bands are much thinner than the normal conduction band, tilting the mini-band significantly reduces its horizontal width. When this width becomes less than an electron's mean free path, the electron will oscillate (Bloch oscillations) between the upper and lower edge of the miniband until it can emit a phonon (Fig. 4b,c). Thus, the average drift velocity of an electron decreases with increasing applied electric field (Fig. 5), giving the I-V curve a negative resistance region[1].

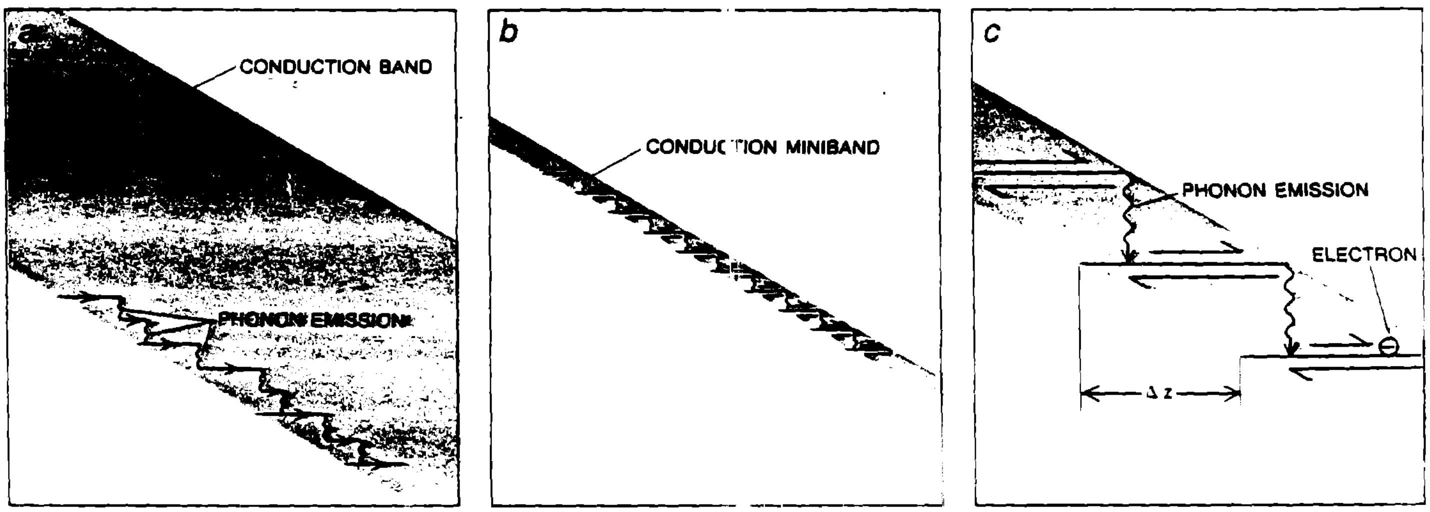


Figure 4 Mini-band conduction (a) and Bloch oscillations (b,c).

As the applied field increases, the electrons become more and more localized, until mini-band to mini-band tunneling becomes possible. Mini-band to mini-band tunneling is possible when the barrier width is thin, and the lowest conduction mini-band aligns with a higher energy mini-band. Due to inhomogeneities, mini-band to mini-band tunneling will be localized in the superlattice. That is, part of the lattice will undergo mini-band conduction and part will undergo mini-band to mini-band tunneling (Fig. 6b,c). As the applied field is increased, more and more of the layers will switch to mini-band to mini-band tunneling, resulting in a number of peaks in the I-V curve. The locations of the peaks in figure 6 are more evident by looking at the derivative of the curve.

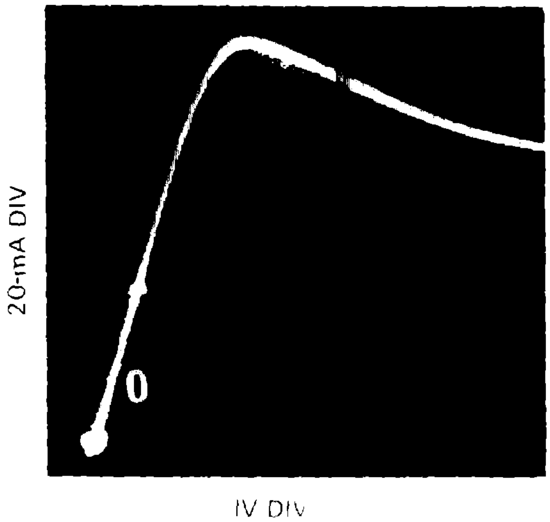


Figure 5 Experimental verification of the negati‹e resistance in the mini-band conduction[3].

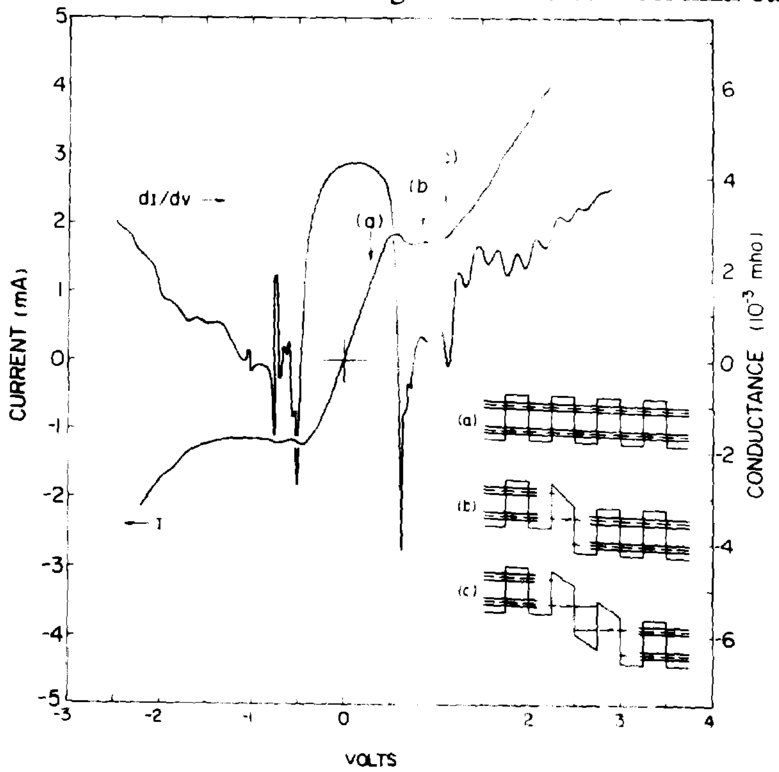


Figure 6 Current-voltage and Conductance voltage characteristics of a superlattice at 77 K. Mini-band conduction (a) and mini-band to nini-band conduction (b and c) are indicated[3].

High field conduction can also take place by mini-band to continuum tunneling and by phonon assisted hopping. Mini-band to continuum tunneling can take place when the applied field is so large that the lowest conduction mini-band alligns with the continuum energy levels above the top of the neighboring quantum well (Fig. 7a). Phonon assisted hopping consists of an electron absorbing a phonon that lifts it into the continuum, band conduction of the electron in the continuum and then emission of a phonon by the electron to drop it down into the next quantum well (Fig. 7b). Thus, the electron "hops" over the potential barrier.

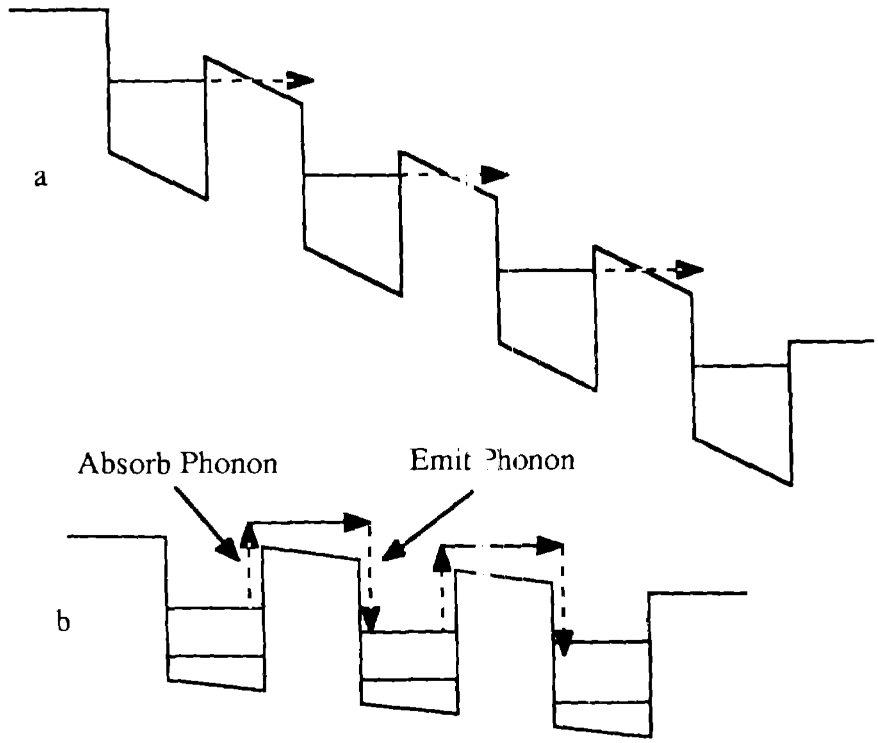


Figure 7 Mini-band to contunuoum tunneling (a) and phonon assisted hopping (b).

OPTICAL PROPERTIES

Optical transitions occur in a superlattice much in the same way as in a conventional semiconductor. An electron is lifted from the valence band across the forbidden gap into the conduction band. However, there are some modifications. First, the transition is now from the highest mini-band in the valence band to the lowest mini-band in the conduction band. Second, there can also be transitions from mini-band to mini-band in the conduction band. Since the locations of the mini-bands are determined by the layer composition and thickness, the effective width of the forbiddden gap becomes adjustable. Thus, the absorption edge (the lowest energy photon that can be absorbed) is now adjustable.

DEVICES USEFUL TO THE LABORATORY

The number of different devices that can be fabricated with a superlattice structure is quite large, with new applications being added every day. There are a large number of applications for semiconductor lasers for optical communications that will not be covered here. We will discuss optical and radiation detectors, high energy light sources, electron multipliers and microwave focusing and detection.

ELECTRON MULTIPLIER

A solid state electron multiplier[4] can be fabricated with a GaAs-$GaAl_xAs_{1-x}$ graded gap superlattice. Figure 8 shows the grading of the composition of the $GaAl_xAs_{1-x}$ barrier layer from pure GaAs to $GaAl_xAs_{1-x}$ with a sharp transition back to GaAs. The conduction band discontinuity is 0.48 eV and the valence band discontinuity is 0.08 eV. When an electric field is applied to this structure, it will look like that in figure 7b. An electron traversing this structure will traverse the graded barrier region with relatively constant energy, and then gain energy when it drops over the edge (the sharp transition back to GaAs).

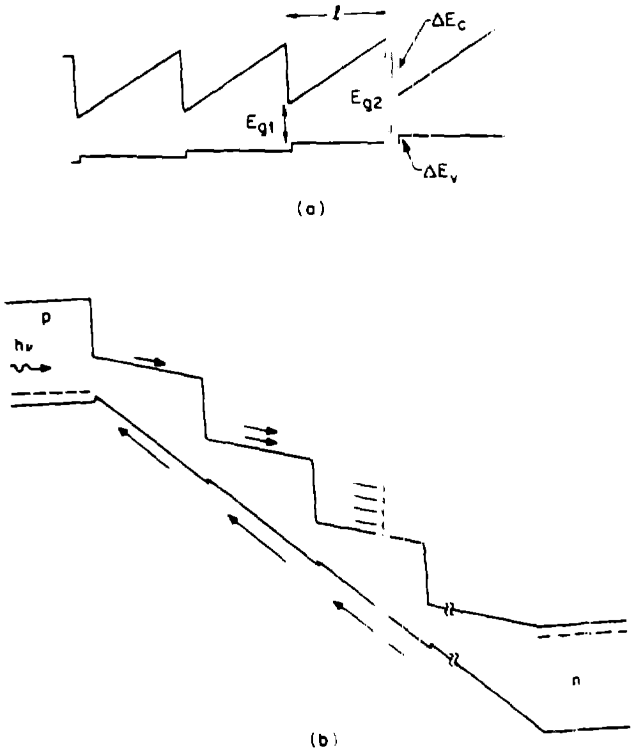


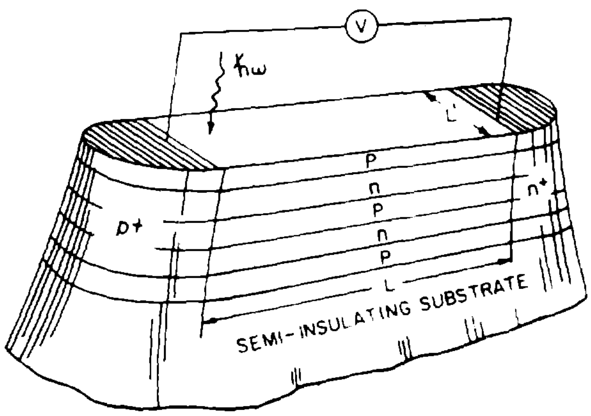
Figure 8 Configuration (a) and operation (b) of a superlattice electron multiplier.

If the device is biased such that the electron's energy is just below the avalanche energy, then the small amount of energy gained as it drops off of the edge of the conduction band will be enough to cause avalanche generation just beyond the edge. The electrons will then traverse a new graded barrier region, drop off the edge and cause more avalanche generation. This effect is similar to the operation of a tube type electron multiplier, where the electrons move from plate to plate. Since the valence band discontinuity is much smaller than the conduction band discontinuity, there will be little hole avalanching.

An extremely low noise electron multiplier results from this confuguration because electrons avalanche at discrete points and holes avalanche very little . Note that it would operate at low voltages (i.e. 5 V) rather than the hundreds of volts required for a conventional electron multiplier.

CHANNELING DIODE

A channeling diode photon detector[4] is fabricated as shown in figure 9a. Using two different semiconductor materials, doped n-type and p-type, a superlattice is built up. Then n^+ and p^+ contact regions are put on the ends and a field is applied. Conduction in this device is in the plane of the superlattice rather than perpendicular to it. Figure 9b shows the bandstructure of the superlattice part of this device. Note that it is a type I' superlattice. Electrons generated in the n-type material will move down into the p-type valley in the conduction band while holes will move up into the n-type peak in the valence band. Thus, electrons and holes are physically separated in this device making for a long lifetime.



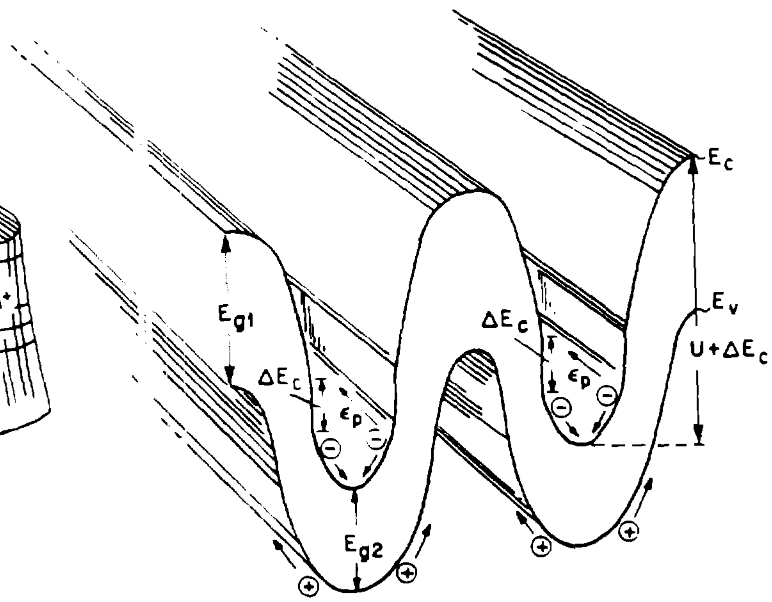


Figure 9 Channeling diode design (a) and band structure (b).

Doping the n-type region more strongly than the p-type region will create a situation where the p-type region has a large electron density (sliding down from the n-type region) and a high mobility (due to the low doping density). The n-type region will be just the opposite, with a low hole density and a low mobility. This results in a high conductivity p-type region for electrons and a low conductivity n-type region for holes.

The materials were chosen for the device so that the p-type region has a smaller band gap than the n-type region. Thus, the electron avalanche generation coefficient (α) in the p-type region will be larger than the hole avalanche generation coefficient (β) in the n-type region. Thus, the α/β ratio will be increased, decreasing the noise of the detector compared with a bulk avalanche diode detector.

Compared to a standard bulk avalanche detector, this device will have longer lifetime, higher electron conductivity and enhanced α/β ratio. Performance wise, it will have much less noise and higher gain.

NARROW BAND IR DETECTOR

By coupling a quantum well to a superlattice, a narrow band infrared detector can be created[5]. Photons are absorbed in the quantum well and excite electrons from the ground state to the first excited state. The quantum well is designed so that it will have a sharply defined ground state, and so that the first excited state falls in the lowest conduction mini-band of the adjacent superlattice (Fig. 10).

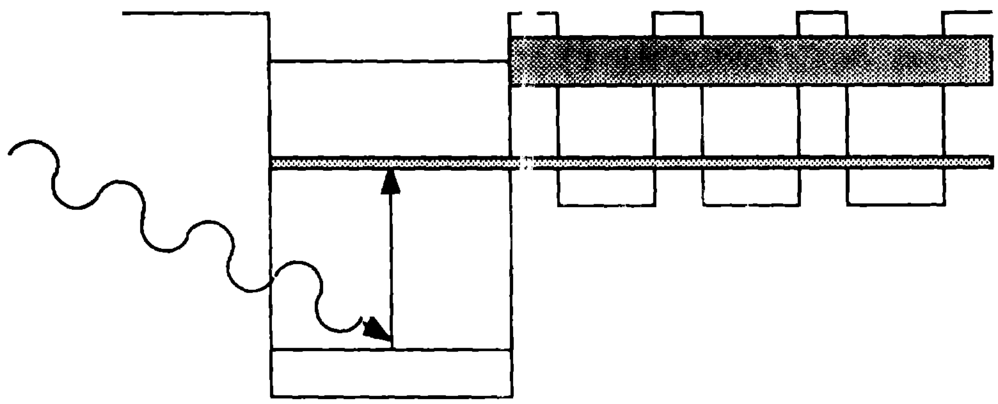


Figure 10 A narrow band infrared detector

By changing the quantum well dimensions, you can change the energy difference between the ground state and the first excited state of the quantum well, making the center frequency for the absorber an adjustable quantity. Changing the width of the barrier layers in the superlattice will change the width of the lowest energy mini-band. The width of this mini-band determines the width of the absorption peak (detector bandwidth) making this also an adjustable quantity. Figure 11 shows some calculated absorption curves for this configuration.

X-RAY MONOCHROMATOR

An x-ray monochromator has been fabricated[6] using alternating layers of tungsten (7 Å) and carbon (14.3 Å). The device operates by using Bragg diffraction of the x-rays at the superlattice planes.

UV OR X-RAY LIGHT SOURCE

A hard ultraviolet or soft x-ray light source can be made with a superlattice by passing an electron beam down its length[7]. The source of the light is transition radiation as the electrons pass from one material to another. Light sources of this type have been made here at the lab using thin metal foils however, relativistic electrons are needed to generate the light. Because a superlattice can be made so much smaller than a stack of metal foils, a relativistic electron beam is no longer needed. Relativistic electrons are generated using accelarators that can take up the space of a small building or more, while a nonrelativistic electron beam can be generated with a bench top power supply. This is a considerable savings in material and space. Coherent light can also be generated with this structure, but that requires sub-picosecond pulses of electrons

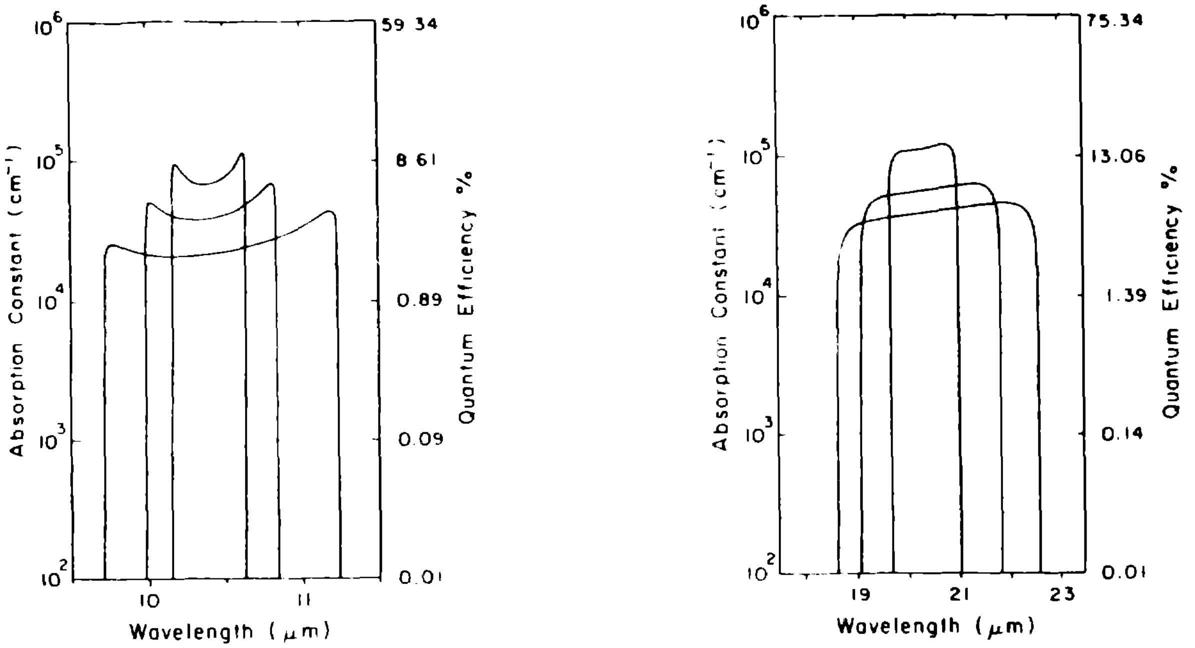


Figure 11 Calculated response of a narrow and infrared detector.

<u>OPTICAL MODULATOR / MICROWAVE DETECTOR</u>

An optical modulator can be made with a superlattice. The bandgap of a superlattice can be changed with an applied electric field. Since the optical absorption coefficient of a device is controlled by the bandgap, this electric field can be used to modulate an optical beam. If a microwave is used as the driving field, then the device will function as a microwave detector.

CONCLUSIONS

In this paper, we have described the basics of solid state superlattice design and operation, and have determined several applications that would be of benefit to the laboratory. The solid state superlattice is a unique material for fabricating solid state devices. This uniqueness stems from capability to design a material with specific semiconductor properties rather than being stuck with the properties of a particular material. This adjustability is obtained with the composition, doping and layer thickness of the solid state superlattice. Fabrication is currently possible to a high degree of precision with molecular beam epitaxy, a technology that we are currently acquiring. Devices that would be useful to the laboratory programs consist primarily of photon detectors (optical, IR, microwave, x-ray, etc.), light sources and optical switches. However, more and more applications are appearing in the literature daily which might also prove useful.

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